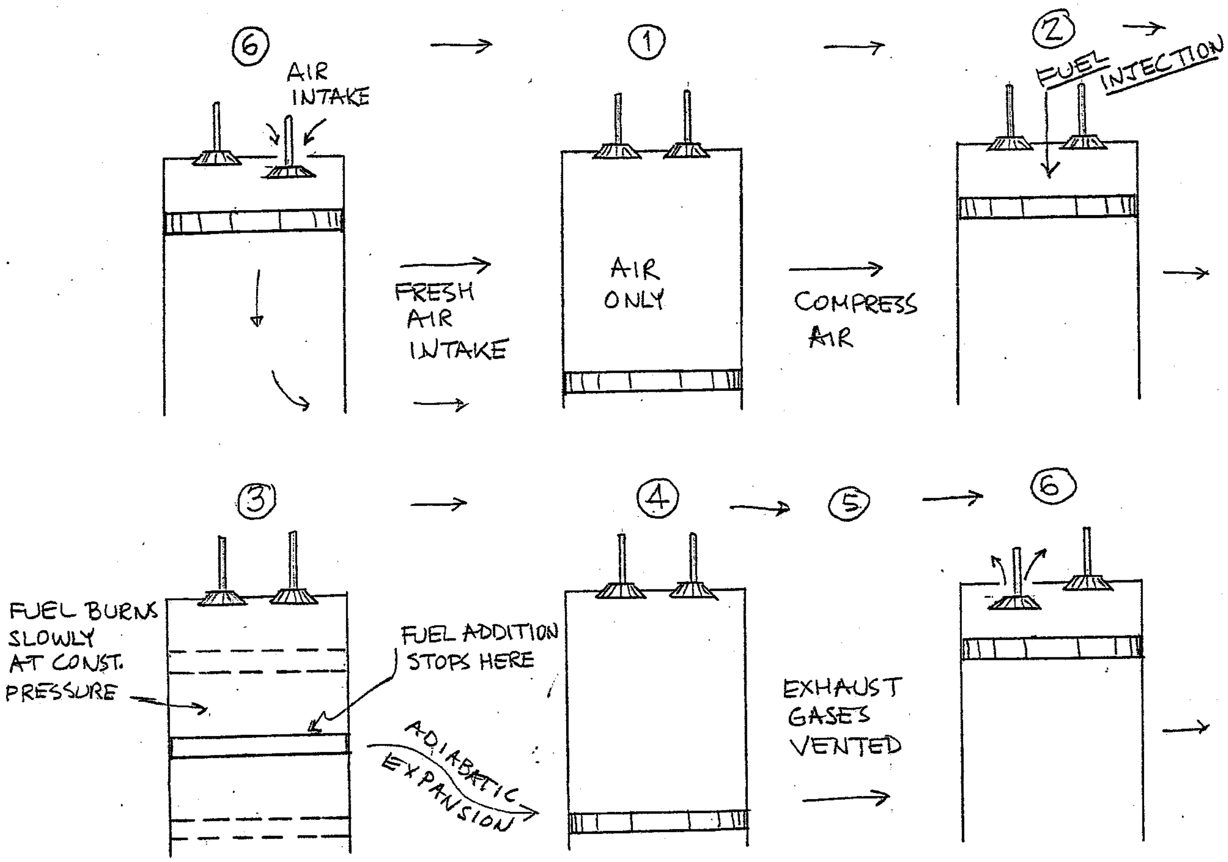
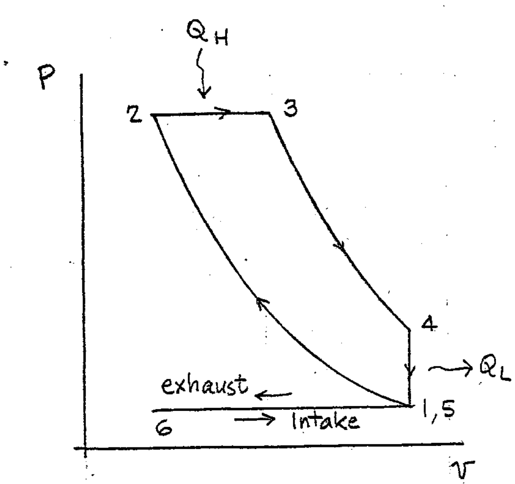
Diesel Engine Cycle

The diesel engine is a four-stroke internal combustion engine. Combustion of the air-fuel mixture occurs through compression ignition.



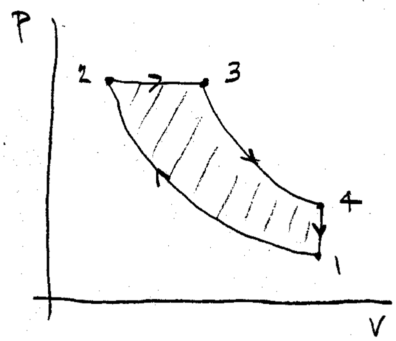


$r_v = \frac{V_1}{V_2}$ volumetric compression ratio

$r_c = \frac{V_3}{V_2}$ cut off ratio

DIESEL Cycle

Consider next the Diesel cycle



The Diesel cycle consists of: 4 processes

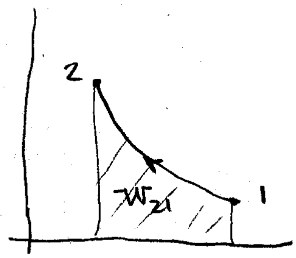
1–2: compression (adiabatic)

2–3: heat addition, expansion

3–4: expansion (adiabatic)

4–1: heat rejection

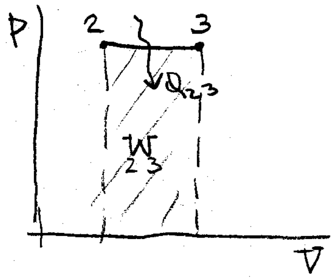
Process 1–2. Compression occurs ADIABATICALLY.



$$Q_{12} = 0$$

$$W_{12} = -\Delta_{12} U = -mc_v(T_2 - T_1)$$

Process 2–3. Heat addition at constant pressure



$$W_{23} = \int_2^3 p\,dV = p_2 \int_2^3 dV = p_2(V_3 - V_2)$$

$$= mR(T_3 - T_2)$$

NOTE: $p_2 = p_3 = \text{const.}$

$$\Delta_{23} U = Q_{23} - W_{23}$$

$$Q_{23} = \Delta_{23} U + W_{23} = mc_v(T_3 - T_2) + p_2(V_3 - V_2)$$

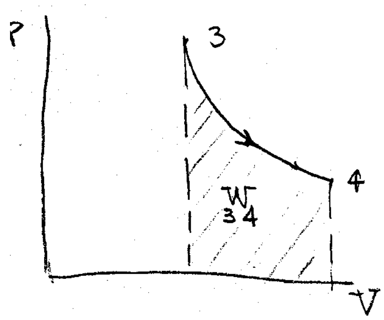
$$= mc_v(T_3 - T_2) + p_3 V_3 - p_2 V_2$$

NOTE: $p_2 = p_3$

$$Q_{23} = mc_v(T_3 - T_2) + mRT_3 - mRT_2 = m(c_v + R)(T_3 - T_2)$$

$$= c_p(T_3 - T_2)$$

Process 3–4 ADIABATIC expansion

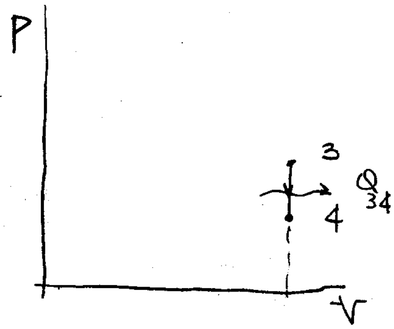


$$Q_{34} = 0$$

$$W_{34} = -\Delta_{34} U = -mc_v(T_4 - T_3)$$

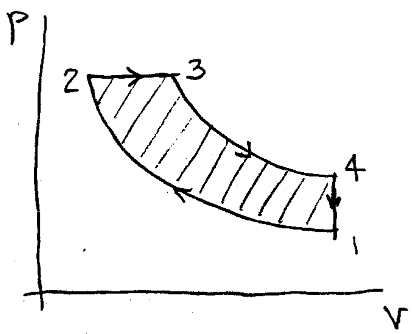
Process 4-1 Heat rejection at constant volume.

$V_3 = V_4 \quad \therefore \quad W_{34} = 0$



$$Q_{34} = \Delta_{34} U = m c_v (T_4 - T_3)$$

Summary of the cycle:



Net work

$$W_{net} = W_{12} + W_{23} + W_{34} + W_{41}^{\nearrow 0}$$

$$W_{net} = -mc_v(T_2 - T_1) + mR(T_3 - T_2) - mc_v(T_4 - T_3)$$

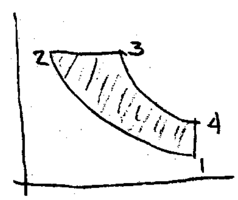
$$Q_{in} = Q_{23} = m(c_v + R)(T_3 - T_2)$$

Thermal efficiency

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{mR(T_3 - T_2) + mc_vT_3 - mc_vT_4 - mc_vT_2 + mc_vT_1}{m(c_v + R)(T_3 - T_2)}$$

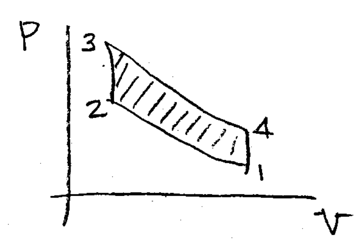
$$= \frac{m(c_v + R)(T_3 - T_2) - mc_v(T_4 - T_1)}{m(c_v + R)(T_3 - T_2)}$$

$$\boxed{\eta_{th} = 1 - \frac{c_v(T_4 - T_1)}{(c_v + R)(T_3 - T_2)}} \longleftarrow \text{DIESEL CYCLE}$$



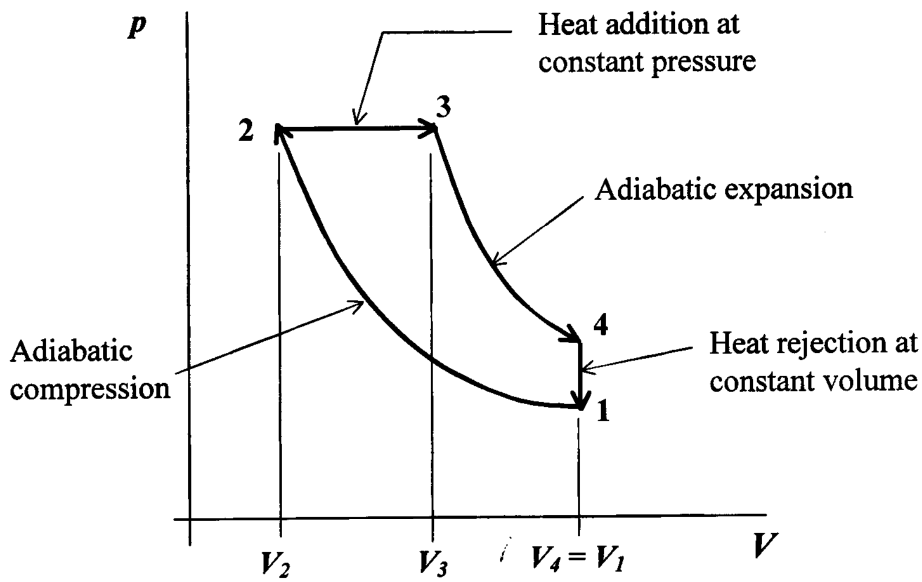
Compare with Otto cycle

$$\boxed{\eta_{th} = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)}} \longleftarrow \text{OTTO CYCLE}$$



Consider and ideal Diesel engine cycle in which the pressure and temperature at the beginning of the adiabatic compression process are 100 kPa and 27°C, the volumetric compression ratio is 18 ($r_v = v_1/v_2 = 18$), and the cutoff ratio for the cycle is 2 ($r_c = v_3/v_2 = 2$). Analyze each of the four processes in this cycle for work and heat transfer, state variables, and determine the thermal efficiency. Conduct your calculations assuming constant specific heat capacity as given below.

Assume the working fluid is air with $c_v = 0.718$ kJ/kg-K, cp = 1.005 kJ/kg-K, k = 1.4
R = 0.287 kJ/kg K



State	p (kPa)	v (m^3/kg)	T (°C)	Process	Δu (kJ/kg)	q (kJ/kg)	w (kJ/kg)
1	100		27	1-2			
2				2-3			
3				3-4			
4				4-1			
				TOTAL			

Cycle efficiency:

Diesel Cycle Example calculation

Initial conditions are given in terms of the initial pressure, temperature, the volume compression ratio, v1/v2 = 18, and the cutoff ratio, v3/v2 = 2.

Units setup: $kJ := 10^3 \cdot J$ $kPa := 10^3 \cdot Pa$

The system is air with the following properties: $R := 0.287 \cdot \frac{J}{gm \cdot K}$ $c_v := 0.718 \cdot \frac{J}{gm \cdot K}$ $k := 1.40$

Given information $p_1 := 100 \cdot kPa$ $T_1 := 300 \cdot K$ $r_v := \frac{v_1}{v_2}$ $r_v := 18$ $r_c := \frac{v_3}{v_2}$ $r_c := 2$

Calculation of v1 from the ideal gas relationship pv = RT. $v_1 := \frac{R \cdot T_1}{p_1}$ $v_1 = 0.861 \frac{m^3}{kg}$

Process 1 - 2: Adiabatic compression. $q_{12} := 0 \cdot \frac{kJ}{kg}$

$v_2 := \frac{v_1}{r_v}$ $v_2 = 0.048 \frac{m^3}{kg}$ $p_2 := p_1 \cdot \left(\frac{v_1}{v_2}\right)^k$ $p_2 = 5.72 \times 10^6 \, Pa$ $T_2 := \frac{p_2 \cdot v_2}{R}$ $T_2 = 953.301 K$

Calculation of work $w_{12} := \frac{p_2 \cdot v_2 - p_1 \cdot v_1}{1 - k}$ $w_{12} = -468.744 \frac{kJ}{kg}$

Calculation of internal energy change from the first law $\Delta u_{12} := -w_{12}$ $\Delta u_{12} = 468.744 \frac{kJ}{kg}$

Note that work can be calculated directly from its integral expression $w_{12} = \int_{v_1}^{v_2} p(v) \, dv$

where $p(v) := p_1 \cdot \left(\frac{v_1}{v}\right)^k$ $w_{12} := \int_{v_1}^{v_2} p(v) \, dv$ $w_{12} = -468.744 \frac{kJ}{kg}$

Process 2 - 3: Heat addition at constant pressure: $p_3 := p_2$ $p_3 = 5.72 \times 10^3 \, kPa$

$v_3 := r_c \cdot v_2$ $v_3 = 0.096 \frac{m^3}{kg}$

From the ideal gas law equation of state: $T_3 := \frac{p_3 \cdot v_3}{R}$ $T_3 = 1.907 \times 10^3 \, K$

Calculation of work $w_{23} := p_2 \cdot (v_3 - v_2)$ $w_{23} = 273.598 \frac{kJ}{kg}$

Calculation of internal energy change $\Delta u_{23} := c_v \cdot (T_3 - T_2)$ $\Delta u_{23} = 684.47 \frac{kJ}{kg}$

Calculation of heat transfer from the first law $q_{23} := \Delta u_{23} + w_{23}$ $q_{23} = 958.068 \frac{kJ}{kg}$

Process 3 - 4: Adiabatic expansion. $q_{34} := 0 \cdot \frac{kJ}{kg}$

$v_4 := v_1$ $\quad p_4 := p_3 \cdot \left(\frac{v_3}{v_4}\right)^k$ $\quad p_4 = 2.639 \times 10^5\, Pa$ $\quad T_4 := \frac{p_4 \cdot v_4}{R}$ $\quad T_4 = 791.705\, K$

Calculation of the change in internal energy $\Delta u_{34} := c_v \cdot (T_4 - T_3)$ $\quad \Delta u_{34} = -800.497 \frac{kJ}{kg}$

Calculation of work from the first law $w_{34} := -\Delta u_{34}$ $\quad w_{34} = 800.497 \frac{kJ}{kg}$

Process 4 - 1: Heat rejection at constant volume . $w_{41} := 0 \cdot \frac{kJ}{kg}$

$p_4 := p_1 \cdot \left(\frac{T_4}{T_1}\right)$ $\quad p_4 = 263.902\, kPa$

Calculation of the change in internal energy $\Delta u_{41} := c_v \cdot (T_1 - T_4)$ $\quad \Delta u_{41} = -353.044 \frac{kJ}{kg}$

Calculation of the heat transfer from the first law $q_{41} := \Delta u_{41}$ $\quad q_{41} = -353.044 \frac{kJ}{kg}$

Cycle summation: $q_{net} := q_{12} + q_{23} + q_{34} + q_{41}$ $\quad q_{net} = 605.024 \frac{kJ}{kg}$

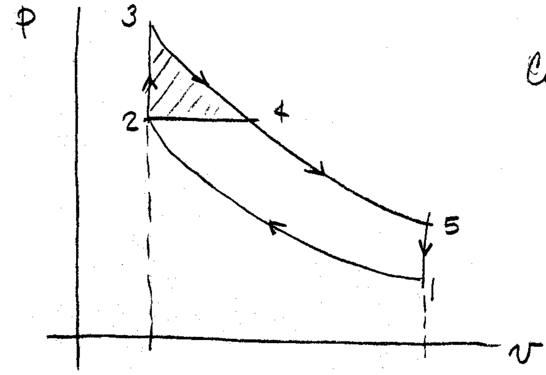
$w_{net} := w_{12} + w_{23} + w_{34} + w_{41}$ $\quad w_{net} = 605.351 \frac{kJ}{kg}$

$\Delta u_{net} := \Delta u_{12} + \Delta u_{23} + \Delta u_{34} + \Delta u_{41}$ $\quad \Delta u_{net} = -0.327 \frac{kJ}{kg}$

Cycle efficiency: $q_{in} := q_{23}$ $\quad q_{in} = 958.068 \frac{kJ}{kg}$

$\eta := \frac{w_{net}}{q_{in}}$ $\quad \eta = 0.632$

Compare the efficiencies of the Otto & Diesel cycles



Compare cycles for the same $\frac{v_1}{v_2}$ ratio.

⇨ Otto: $1 \to 2 \to 3 \to 4 \to 5 \to 1$

⇨ Diesel: $1 \to 2 \to 4 \to 5 \to 1$

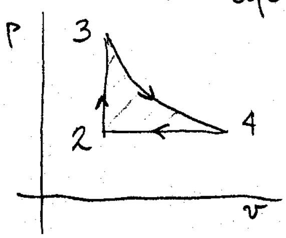
Which cycle does more work? Otto cycle. – The area under the curve 3-4-5 is larger than under 2-4-5, Also the net work (area enclosed by the cycle) is larger.

Efficiencies:

$$\eta_{Otto} = 1 - \frac{T_5 - T_1}{T_3 - T_2} \quad ; \quad \eta_{Diesel} = 1 - \frac{T_5 - T_1}{k(T_4 - T_2)}$$

Compare $(T_3 - T_2)$ with $k(T_4 - T_2)$

Consider the cycle 2-3-4-2 $\quad \Sigma Q = \Sigma W$



$Q_{23} + Q_{42} = W_{34} + W_{42} = W_{net} > 0$ Net positive area

$Q_{23} + Q_{42} > 0$

$Q_{23} > -Q_{42}$ but $-Q_{42} = Q_{24}$

$\therefore Q_{23} > Q_{24}$

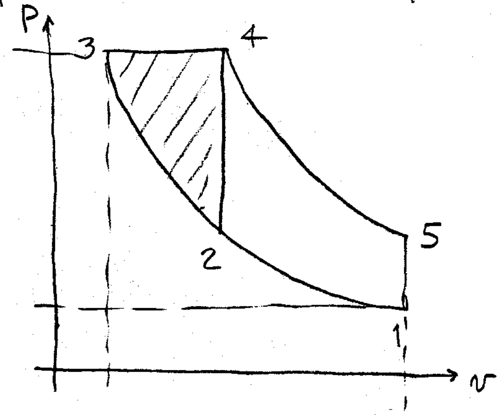
$c_v(T_3 - T_2) > c_p(T_4 - T_2)$

$(T_3 - T_2) > k(T_4 - T_2)$

Hence $\frac{T_5 - T_1}{T_3 - T_2} < \frac{T_5 - T_1}{k(T_4 - T_2)}$ and $1 - \frac{T_5 - T_1}{T_3 - T_2} > 1 - \frac{T_5 - T_1}{k(T_4 - T_2)}$

Finally $\underline{\eta_{Otto} > \eta_{Diesel}}$

Compare the work and efficiency of the Otto and Diesel cycles for the same pressure ratio $P_3/P_1 = P_4/P_1$

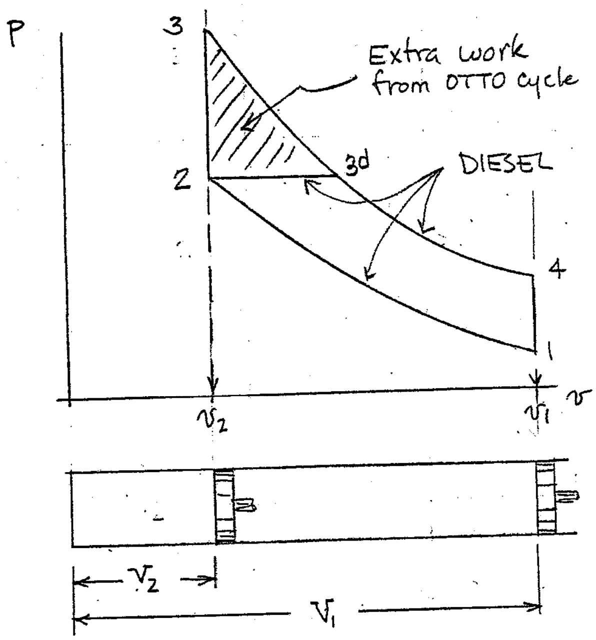


⇨ Otto : $1 \to 2 \to 4 \to 5 \to 1$

⇨ Diesel : $1 \to 2 \to 3 \to 4 \to 5 \to 1$

Comparison between Otto (gasoline) and Diesel engines

Same compression ratio



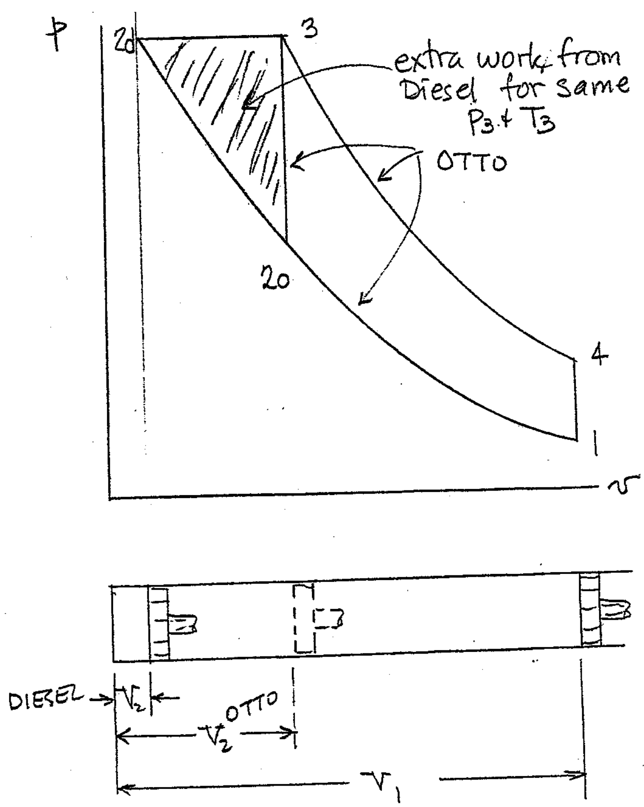
$\eta_{OTTO} > \eta_{DIESEL}$

$\eta = 1 - \frac{Q_L}{Q_H}$

$(Q_L)_D = (Q_L)_O$

$(Q_H)_D < (Q_H)_O$

BUT !! Diesel engines operate at much higher compression ratios



$\eta_{OTTO} < \eta_{DIESEL}$

$\eta = 1 - \frac{Q_L}{Q_H}$

$(Q_L)_O = (Q_L)_D$

$(Q_H)_D > (Q_H)_O$